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DEVELOPMENT AND TESTING OF IMPROVED POLYIMIDE ACTUATOR ROD SEALS AT HIGHER TEMPERATURES FOR USE IN ADVANCED AIRCRAFT HYDRAULIC SYSTEMS

by

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16. Abstract

Polyimide second-stage rod seals developed during the NAS3-14317 contract were evaluated to determine their suitability for applications in advanced aircraft systems. The 6.35 cm (2.5 in.) K-section seal and the 2.54 cm (1.0 in.) Chevron seal were verified for higher temperature applications than those considered in the initial seal design. These seals completed 5.8×10^6 cycles, equivalent to 6750 hours of flight operation at system temperatures of 478° K (400° F) and 3125 hours of flight operation at 505° K (450° F).

External rod seal leakage was generally low throughout these tests, less than the maximum allowable two drops per 25 cycles. At program completion, the seals showed no signs of structural degradation. Post-test inspection showed the seals retained a snug fit against the shaft and housing walls, indicating additional wear life capability.

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SUMMARY

The objective of the program conducted under NASA contract NAS3-16733 was to continue development of polyimide second-stage rod seals developed during the NAS3-14317 contract for application to advanced aircraft systems. This objective was accomplished by verifying the 6.35 cm (2.5 in.) K-section seal and the 2.54 cm (1.0 in.) chevron seal capability for higher temperature applications required by type III hydraulic systems.

Adequate fatigue and wear life were verified in cycling tests of a linear hydraulic actuator with simulated loads and environmental conditions. Linear cycling, 3.85×10^6 cycles, equivalent to 6250 hr of advanced aircraft flight operation at 478° K (400° F) and additional linear cycling, 1.925×10^6 cycles, equivalent to 3125 hr of advanced aircraft flight operation at 505° K (450° F) were completed by a single 6.35 cm (2.5 in.) K-section seal and a single 2.54 cm (1.0 in.) chevron seal. Both seal configurations demonstrated low leakage characteristics during test. Each seal did experience erratic external leakage for a short test period due to heavy fluid residue deposits on the actuator rod being run through the sealing surface. Leakage returned to a low value after these fluid residue deposits were removed. No structural degradation of either the upstream or downstream sealing elements occurred in either seal configuration.

It was concluded from the testing completed during this program that polyimide seals have satisfactory operational capability over a wider temperature range than most seals in present usage. The test results demonstrated that, by careful designing, polyimide second-stage rod seals can be made to satisfy the dynamic hydraulic actuator requirements of applications in high-performance aircraft.

Tests should be continued to evaluate the K-section and chevron second-stage seal configurations with other fluids and environments to further expand the field of knowledge regarding the application of these seals to satisfy the ever-expanding demands for reliable methods of fluid containment.

INTRODUCTION

Development of advanced aircraft systems requires consideration of new materials and design concepts for hydraulic systems. The higher fluid temperatures identified with these hydraulic systems precludes the use of many heretofore conventional design practices. The universal application of the elastomer to all hydraulic sealing applications is a thing of the past. The elastomers used in conjunction with polytetrafluoroethylene (PTFE) seal components will still have specific design applications, but critical dynamic sealing requirements will require new materials capable of long life at high fluid temperatures.

The material properties of polyimides are acceptable for the entire range of type III hydraulic system temperatures as well as for considerably higher temperatures, making these materials prime candidates for experimental seal research for advanced aircraft applications. Experimental investigations with polyimides to date have emphasized these materials' stable strength properties at high temperatures over long durations. NASA-initiated research was instrumental in the early development of new seal concepts using polyimides in exploratory tests to determine sealing characteristics under various operating environments. These efforts were conducted under the NAS3-7264, NAS3-11170, and NAS3-14317 contracts, references 1, 2, and 3, respectively.

The program reported herein is a continuation of the above-mentioned seal development programs. It was intended to verify second-stage rod seal performance for higher temperature applications than those previously considered. The developed seals were required to function at simulated loads representative of an advanced aircraft and in long-term fatigue/wear tests representative of required mean time between overhaul periods for an advanced aircraft. Test operation was conducted at actuator temperatures equivalent to a type III hydraulic system (219° to 505° K, -65° to +450° F).

SEAL ENDURANCE TESTS

The objective of this program was to continue evaluation of second-stage polyimide rod seal designs developed for advanced aircraft applications. The continued evaluation was to determine K-section and chevron seal performance in fluid operating temperature conditions of 478° K (400° F) and 505° K (450° F). The seal design under test was established in the NAS3-14317 contract, reported in reference 3, for operation at a design temperature of 450° K (350° F).

SEALS TESTED

The test articles were the 6.35 cm (2.5 in.) K-section second-stage seal and the 2.54 cm (1.0 in.) chevron second-stage seal as designed under NASA contract NAS3-14317, see reference 3 and appendix A. Both test articles were fabricated from Dupont SP-21 polyimide material per Boeing drawing, references 4 and 5. Seal cavities were per reference 6 except for the piston rod diameters. The 6.347 cm (2.499 in.) rod diameter for the 6.35 cm (2.5 in.) seal was established for testing at 478 K (400° F). This rod diameter was not increased for 505° K (450° F) testing. A 2.540 cm (1.000 in.) rod diameter was established for the 2.54 cm (1.0 in.) seal for 478° K (400° F) testing. This rod diameter was not increased for 505° K (450° F) testing. The increase in rod diameters was required to ensure an interference fit between the rods and seals at the maximum test temperature with the specific dimensions selected so that minimum overstressing of the seals would occur at room temperature. Changes in rod diameters were accepted in preference to redesigning the seals for the increased test temperatures.

The K-section seal was assembled in the module configuration designed under NASA contract NAS3-14317 (ref. 3) and shown in figure 1. The module was installed in the 6.35 cm (2.5 in.) nominal rod actuator as shown in figure 2. The 2.54 cm (1.0 in.) chevron seal was installed directly in the 2.54 cm (1.0 in.) nominal rod actuator end cap as shown in figure 3.

TEST SETUP

Test Apparatus

Existing test actuator components were used to the greatest extent possible. These actuators are defined in references 7 and 8. A cast iron contracting seal was used as the first-stage seal for both actuators. Details of this seal design are shown in appendix B. The first-stage seals were not considered as test articles, although data on first-stage seal performance was obtained.

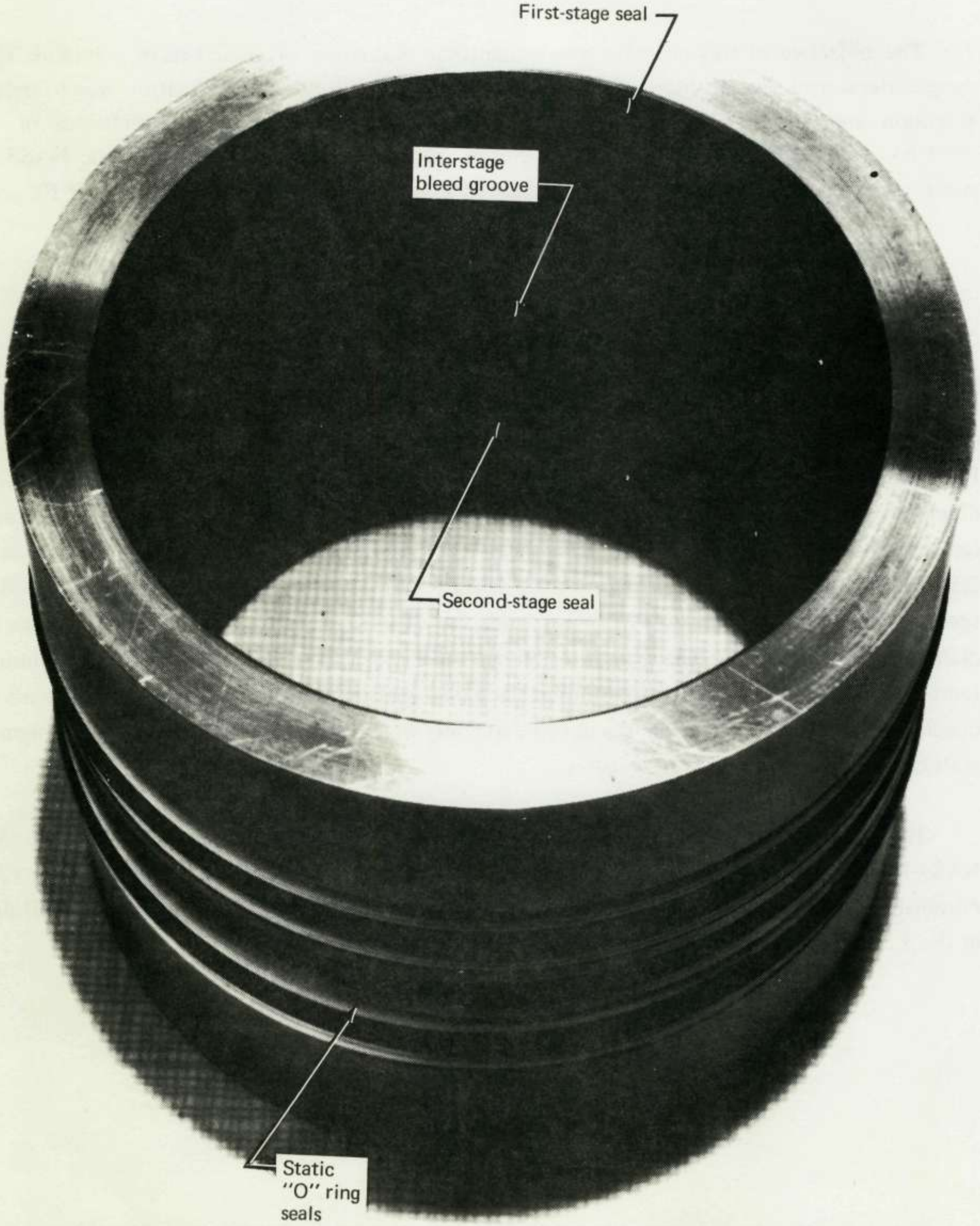


FIGURE 1.–6.35 CM (2.5 IN.) TWO-STAGE SEAL MODULE

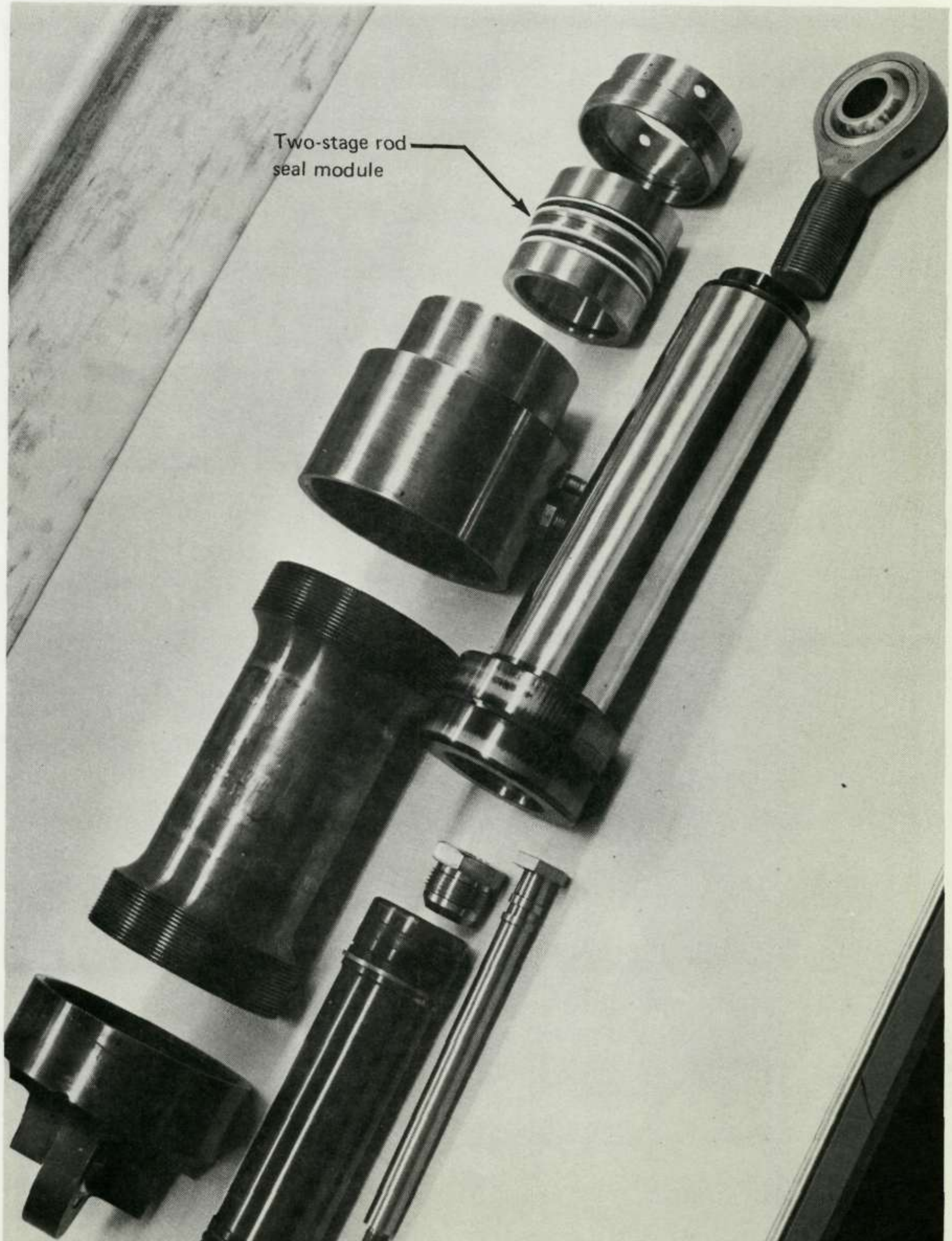


FIGURE 2.—6.35 CM (2.5 IN.) ENDURANCE TEST ACTUATOR

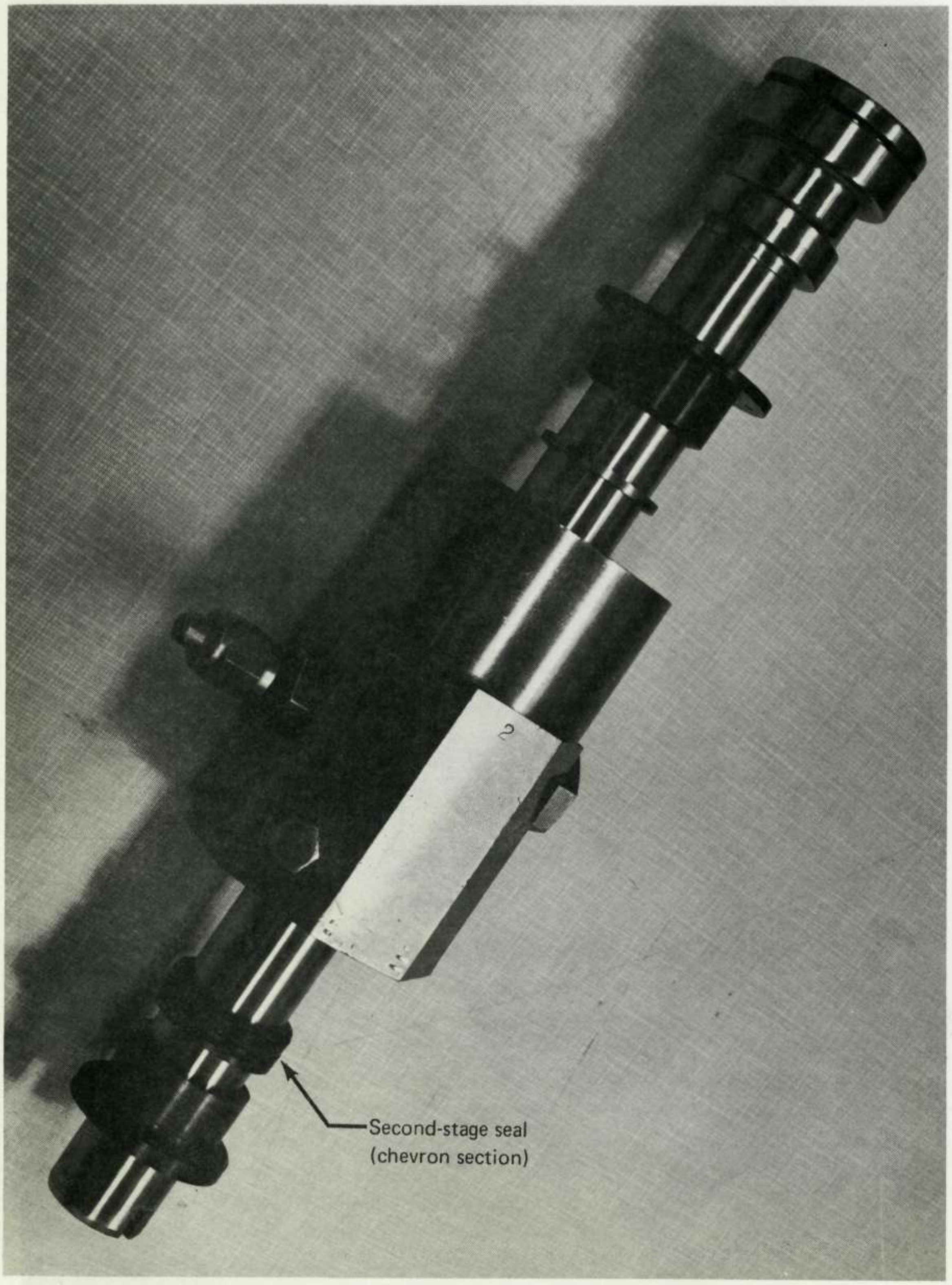


FIGURE 3.—2.54 CM (1.0 IN.) ENDURANCE TEST ACTUATOR

The endurance test installation, shown in figure 4, is an existing rig developed primarily for testing linear actuator seals. The installation consists of a load system, the hydraulic power supply with its associated plumbing, and the control electronics. The major power and loading components are as follows:

Oven-dispatch, model 203

High-temperature power supply—Auto Controls Laboratory, Inc., model 4586

Load fixture—Boeing laboratory equipment

Filter—microporous (25 micron absolute)

Relief valve—Vickers C-175-F

Servovalve block—Boeing laboratory equipment

Accumulator—Hydrodyne 6.895×10^7 N/m^2 (10 000 psig)

The load system consisted of dual torsion bars capable of providing resisting torque for the two independent actuators. The individual torque bar lengths were adjusted to provide a torsional load such as to require full system pressure 2.758×10^7 N/m^2 (4000 psig) at full stroke for each actuator. The force from each linear actuator was reacted to a torsion bar through a lever arm and bearing assembly to simulate an airplane control surface hinge point. Self-aligning bearings were used for both actuators' head end and rod end connection points. No additional side load, other than bearing friction, was applied. The mounting base of the load system and the actuators were installed in a test oven. This installation is shown in figure 5. The torsion bars, due to their size, extended through the back of the oven and were supported externally at their extreme ends by pedestals.

Hydraulic power was supplied by a 1.262×10^{-3} m^3/sec (20 gpm) Auto Controls Laboratory high-temperature power supply. This unit is complete with all pressure and temperature controls. It supplied Humble Oil WS8228 polyolester (ref. 9) hydraulic fluid at 2.758×10^7 N/m^2 (4000 psig) and at the required test temperature. The 9.464×10^{-3} m^3 (2.5 gal) accumulator was located in the supply line between the power supply and the test rig. In addition to filtration within the power supply, a 25-micron-absolute filter was located in the supply line downstream of the accumulator. The cavities between the first- and second-stage seals in the test actuators were vented to return through relief valves to maintain second-stage seal pressure at 1.379×10^6 N/m^2 (200 psig). Additional check and isolation valves allowed measurement of first-stage leakage without interrupting actuator cycling during test.

Control Electronics

The control of test operation cycling was provided by a closed-loop electrohydraulic flow control loop incorporating position feedback.

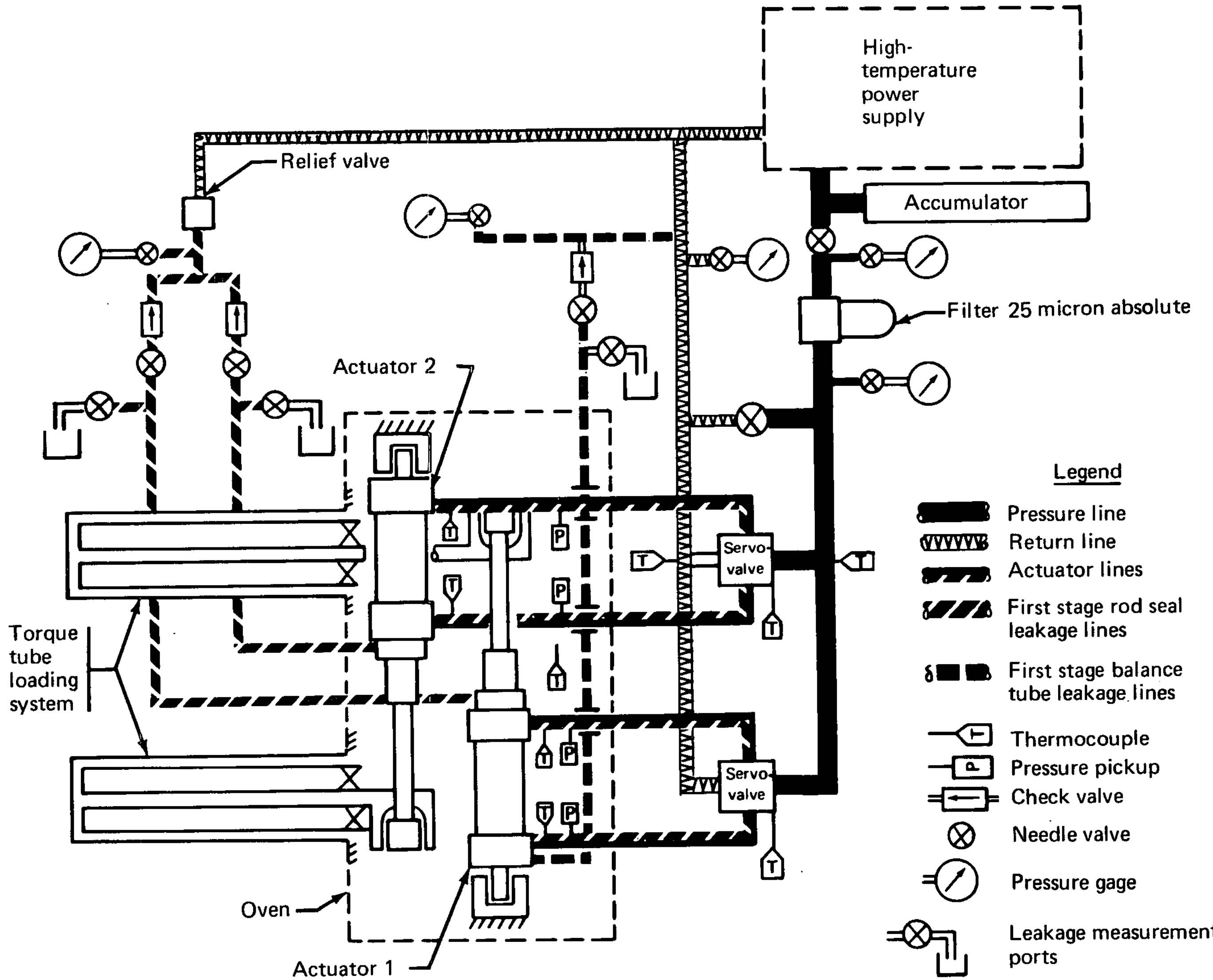


FIGURE 4.–HYDRAULIC INSTALLATION SCHEMATIC, ENDURANCE TEST

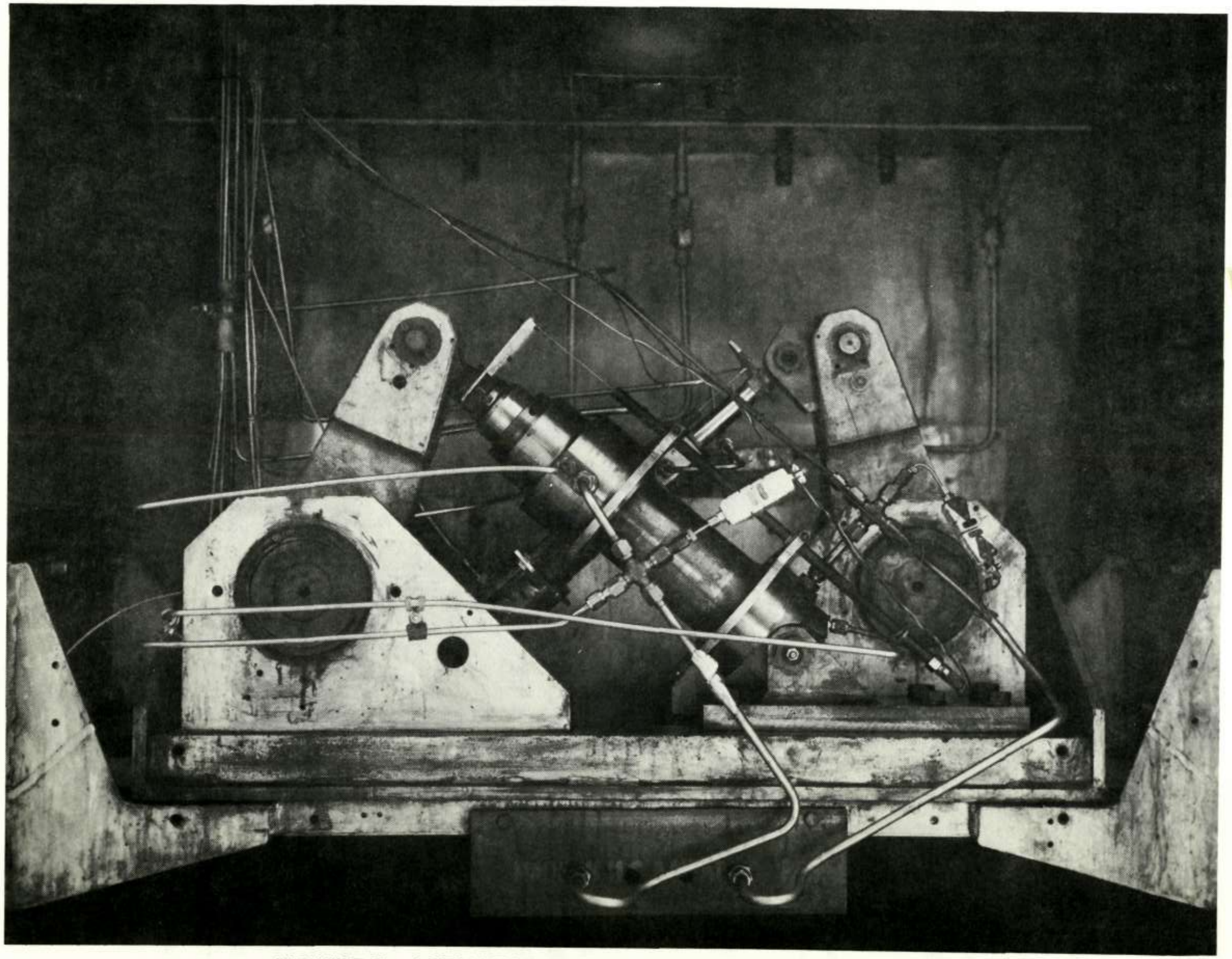


FIGURE 5.—ACTUATOR INSTALLATION, ENDURANCE TEST

Components were arranged as shown in figure 6. The electrical loop consisted of the feedback transducer (LVDT), carrier amplifier, Boeing standard controller, and servovalve with the total loop completed mechanically through the fluid-powered actuator rod. The servocontrollers were driven with a common function generator with a sinusoidal cycle at the required period. The actuator stroke amplitude and position were set at the servocontroller command for the flow control servovalve. A failure detection system was provided which would sound an audible and visual alarm with loss of system pressure or an overtemperature condition.

Actuator head and rod end cylinder pressures were measured for both actuators and recorded on a direct-write oscillograph. The individual actuators' positions were also recorded on the oscillograph and monitored during test to ensure that proper position and stroke amplitudes were maintained.

Oven ambient, oil, and component temperatures were recorded on a stamping-type temperature recorder.

Instrumentation and recorded data accuracies are reported in appendix C.

TEST PROCEDURE

The unpressurized assembled test actuators were manually inspected for binding. A proof pressure was then applied and pretest leakage rates established for the first-stage seals at room temperature.

Test Operation

After the test actuators and data transducers were installed in the loading fixture, a reservoir pressure of 3.442×10^5 N/m^2 (50 psig) was applied and air bled from the hydraulic system. A room temperature checkout was conducted, starting with a system pressure of 6.894×10^6 N/m^2 (1000 psig) and increased in incremental steps to working pressure while cycling. Testing was performed in two categories. The test sequences for each category are defined in tables I and II and were established by adjusting:

- The hydraulic power supply to test temperature and 2.758×10^7 N/m^2 (4000 psig) nominal working pressure

- The oven controls to maintain the test temperature for the mass of the actuators and fixture

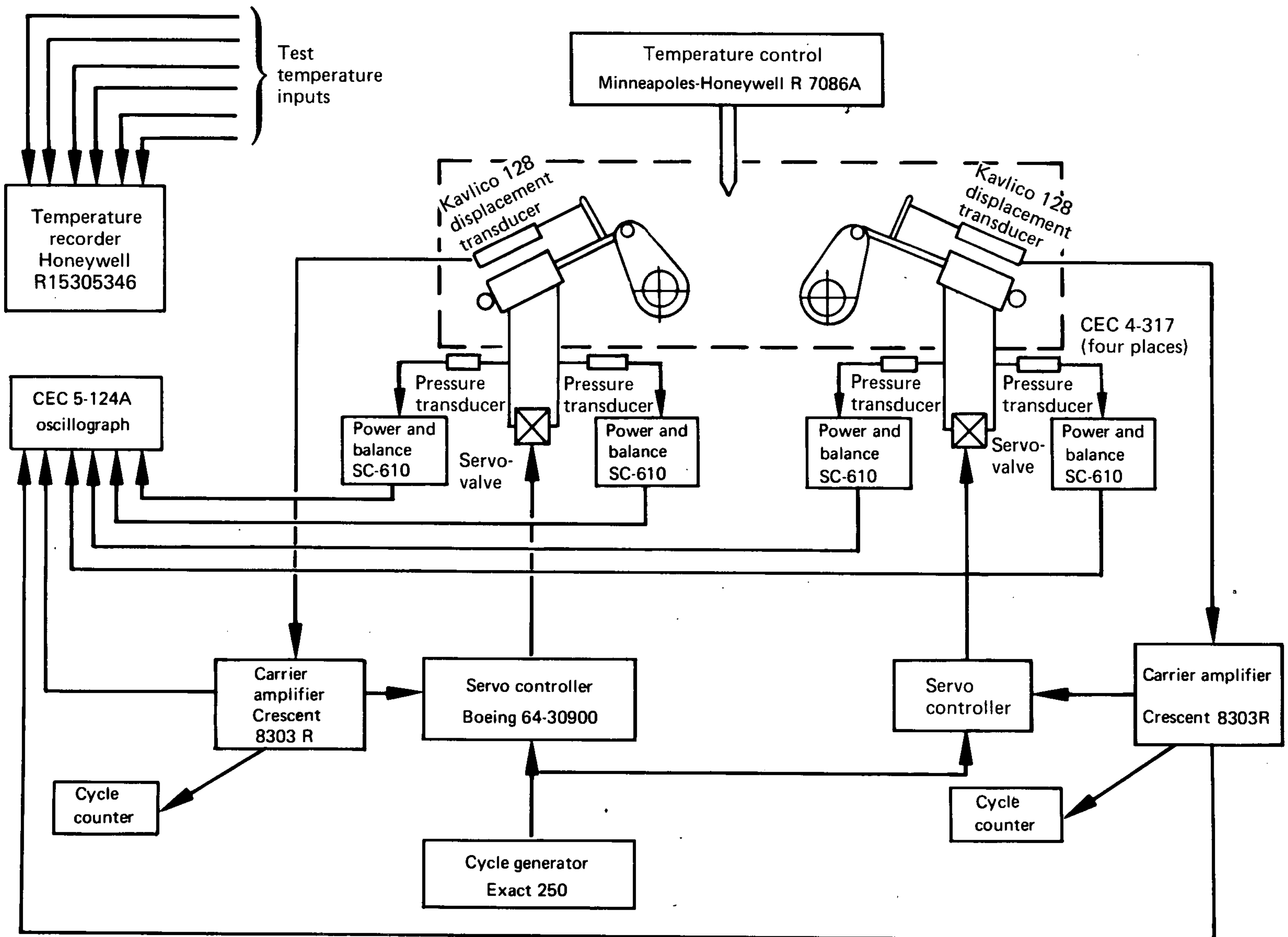


FIGURE 6.—ELECTROHYDRAULIC CONTROL LOOP, ENDURANCE TEST

TABLE I.—ENDURANCE TEST SEQUENCE, CATEGORY 1

Sequence number	Cycles	% load and stroke (see notes 4 and 5)	Maximum cycle rate, Hz	Actuator temperature	
				°K	°F
1	7.5×10^5	2	6	478	400
2	5 000	25	0.83	478	400
3	10 000	50	0.67	478	400
4	5 000	100	0.56	478	400

Notes:

1) All cycles are to be run around actuator midstroke position.
2) A portion of the cycles from sequences 2, 3, and 4 are to be randomly interspersed during performance of sequence 1.
3) Testing spectrum is to consist of five consecutive runs in the sequence shown, i.e., 1, 2, 3, 4, 1, 2, 3, 4, 1, 2 . . . with the sum of sequences 1 + 2 + 3 + 4 equalling one run.
4) 6.35 cm (2.5 in.) actuator: 100% stroke = 7.62 cm (3.0 in.), 100% load = 88 964 N (20 000 lbf)
5) 2.54 cm (1.0 in.) actuator: 100% stroke = 5.72 cm (2.25 in.), 100% load = 22 686 N (5100 lbf)

TABLE II.—ENDURANCE TEST SEQUENCE, CATEGORY 2

Sequence number	Cycles	% load and stroke (see notes 4 and 5)	Maximum cycle rate, Hz	Actuator temperature	
				°K	°F
1	3.75×10^5	2	6	505	450
2	2500	25	0.83	505	450
3	5000	50	0.67	505	450
4	2500	100	0.56	505	450

Notes:

1) All cycles are to be run around actuator midstroke position.
2) A portion of the cycles from sequences 2, 3, and 4 are to be randomly interspersed during performance of sequence 1.
3) Testing spectrum is to consist of five consecutive runs in the sequence shown, i.e., 1, 2, 3, 4, 1, 2, . . . with the sum of sequences 1 + 2 + 3 + 4 equalling one run.
4) 6.35 cm (2.5 in.) actuator: 100% stroke = 7.62 cm (3.0 in.), 100% load = 88 964 N (20 000 lbf)
5) 2.54 cm (1.0 in.) actuator: 100% stroke = 5.72 cm (2.25 in.), 100% load = 22 686 N (5100 lbf)

- The function generator to the cycle rate required by the test schedule
- The servocontroller to provide the desired actuator neutral cycling point and percent of rod stroke
- The interstage relief valve to maintain 1.379×10^6 N/m^2 (200 psig)

During testing, first-stage leakage was measured by its collection in burettes. The second-stage leakage was measured by visual observation.

Post-Test Inspection

The seals that completed endurance tests were examined for structural damage, cracking of the seal material, contact surface polishing, and unusual wear. This was conducted by unaided visual observation supplemented by observations using a microscope.

TEST RESULTS

Category 1

The cycle life defined in table I was completed satisfactorily by the 6.35 cm (2.5 in.) K-section and the 2.54 cm (1.0 in.) chevron seal at 478 K (400°F) while cycling at simulated load conditions. The average leakages obtained during testing, as shown on table III, were all within the allowable 2 drops/25 cycles, except during initial long-stroke conditions of run 4. At the beginning of test during sequence 3 of run 4, the 6.35 cm (2.5 in.) K-section seal exhibited a brief leakage increase. This increase in leakage appeared to be caused by dragging deposits that had accumulated on the actuator rod during short-stroke testing through the second-stage seal. These deposits were primarily built-up layers of residue resulting from air drying of fluid films at the test temperatures during the 188 hr of accumulated short-stroke testing. These deposits were manually removed prior to the long-stroke conditions of run 5, and the erratic leakage did not repeat. The seal leakage decreased to near zero with continued cycling once the seal was cleaned.

A sudden increase in first-stage seal leakage of the 2.54 cm (1.0 in.) rod actuator was also noted during short-stroke cycling in run 5. Subsequent disassembly inspection revealed no discrepancies. This leakage returned to normal after reassembly, indicating that fluid residue deposits on the rod may have caused this leakage in the same manner as with the second stage described above. A photograph of the deposit accumulated on the 2.54 cm (1.0 in.) rod during test is shown in figure 7.

TABLE III.—LEAKAGE DATA, CATEGORY 1 TESTS

Seal configuration	Cycles per test run	Actuator stroke condition	Accumulated cycles per drop of leakage[a]									
			Run 1		Run 2		Run 3		Run 4		Run 5	
			Avg	Max	Avg	Max	Avg	Max	Avg	Max	Avg	Max
6.35 cm (2.5 in.) K-section	7.50×10^5	2%	1800	180	2000	240	3.75×10^5	720	(b)	(b)	(b)	(b)
	0.05×10^5	25%	80	40	(b)	(b)	(b)	(b)	(b)	(b)	(b)	(b)
	0.10×10^5	50%	(b)	(b)	(b)	(b)	(b)	(b)	3.6	1.6	(b)	(b)
	0.05×10^5	100%	(b)	(b)	(b)	(b)	(b)	(b)	(b)	(b)	(b)	(b)
2.54 cm (1.0 in.) chevron	7.50×10^5	2%	600	60	109	26	455	144	2750	180	2000	360
	0.05×10^5	25%	40	40	160	80	40	27	(b)	(b)	(b)	(b)
	0.10×10^5	50%	60	30	75	20	83	30	(b)	(b)	(b)	(b)
	0.05×10^5	100%	(b)	(b)	16.5	10	240	60	(b)	(b)	(b)	(b)

[a]Measurements are indicated as number of cycles per 5×10^{-8} m^3 (number of cycles per drop of leakage). The requirement established for leakage was a minimum of 25 cycles per 10^{-7} m^3 (25 cycles per 2 drops).

[b]No leakage observed during 5-min observation made each 1 hr of test.

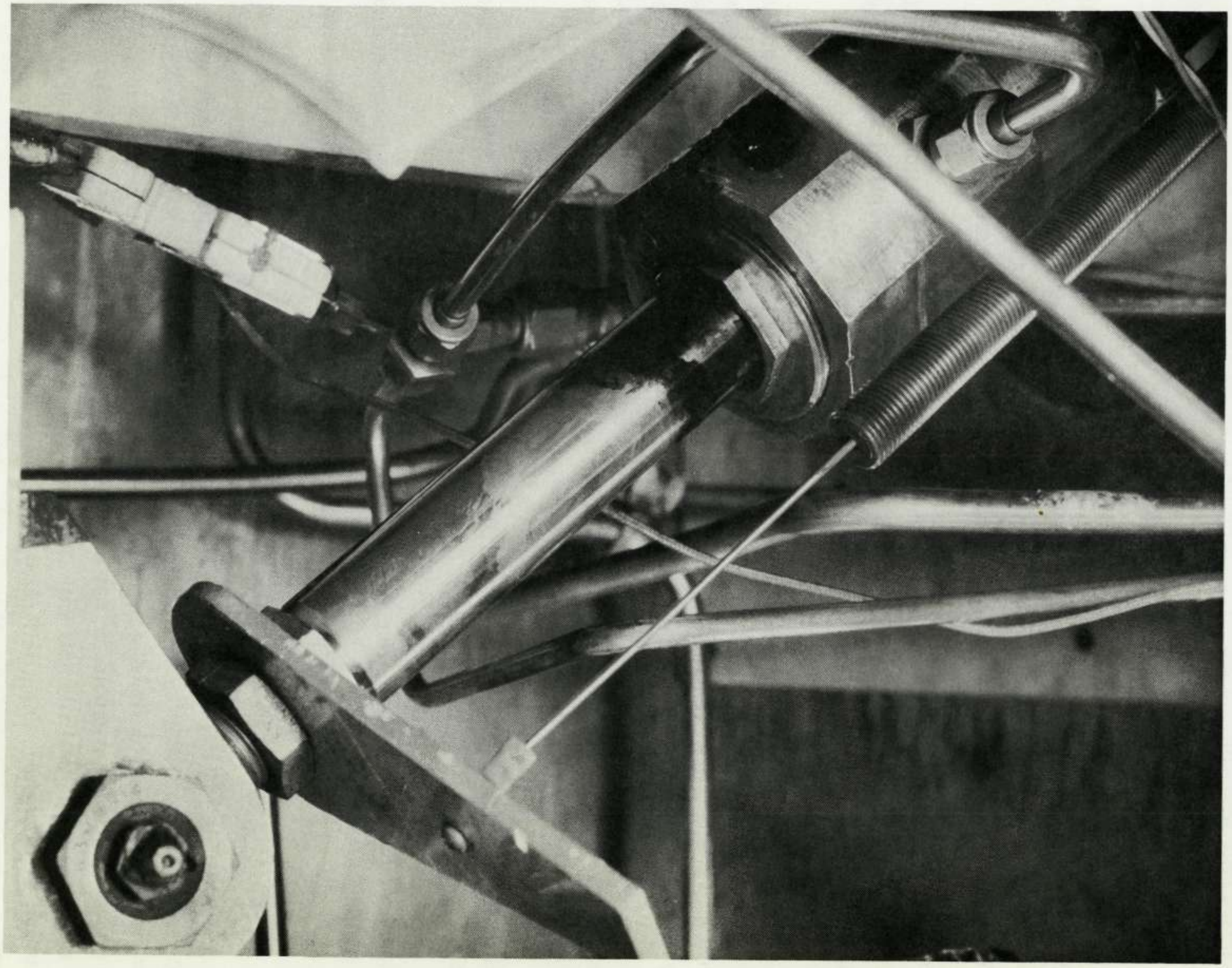


FIGURE 7.–2.54 CM (1.0 IN.) ACTUATOR ROD DURING TESTING AT 478°K (400°F)

Because both the 6.35 cm (2.5 in.) K-section and the 2.54 cm (1.0 in.) chevron second-stage seals performed satisfactorily during category 1 testing at 478° K (400° F), the actuators were not disassembled prior to starting category 2 tests at 505° K (450° F).

Category 2

Room temperature leakage tests performed prior to category 2 tests revealed no leakage during the 15-minute observation period for either the 6.35 cm (2.5 in.) K-section or the 2.54 cm (1.0 in.) chevron seal. The cycle life defined in table II was completed by both actuators at 505° K (450° F). Leakage for the 6.35 cm (2.5 in.) K-section was almost nil during the entire category 2 testing.

Failure of the torsion bar loading system for the 6.35 cm (2.5 in.) test actuator occurred with 900 cycles remaining to test completion. The final 900 cycles were completed at a no-load condition.

Leakage for the 2.54 cm (1.0 in.) chevron seal was low during run 1 and remained low until a sudden increase occurred at the start of the run 2 long-stroke condition (sequence 2). This leakage remained high through all of run 3, started decreasing at the beginning of run 4, and continued low during run 5. These leakage data are shown in table IV. The sudden increase in rod seal leakage may have been influenced by residue deposits on the 2.54 cm (1.0 in.) actuator rod as experienced during category 1. These deposits formed much faster at the 505° K (450° F) conditions and were difficult to remove even after limited thermal exposure.

First-stage seal leakage did not exceed 0.133 cc/sec for either actuator during this test category.

Room temperature leakage testing after completion of category 2 revealed no leakage during the 15-minute observation period.

Disassembly and Inspection

6.35 cm (2.5 in.) K-section seal—The K-section assembly was noted to fit snugly on the actuator rod and in the module cavity. Unusually heavy residue deposits were found on the seal and module cavity. A photograph showing these deposits is shown in figure 8. This residue was evident on the remaining actuator components, but was not unusually heavy as judged by past experience. Visual inspection of the seal assembly with the aid of a microscope revealed no cracks or surface irregularities. The dynamic sealing surfaces were highly polished, with a uniform pattern on both upstream and downstream elements. A detailed description of seal surface condition is shown on figure 9. The actuator rod was in good condition, with only superficial longitudinal marks in the seal running area, figure 10.

TABLE IV.—LEAKAGE DATA, CATEGORY 2 TESTS

Seal configuration	Cycles per test run	Actuator stroke condition	Accumulated cycles per drop of leakage[a]									
			Run 1		Run 2		Run 3		Run 4		Run 5	
			Avg	Max	Avg	Max	Avg	Max	Avg	Max	Avg	Max
6.35 cm (2.5 in.) K-section	3.750×10^5	2%	(b)	(b)	(b)	360	(b)	(b)	720	72	(b)	(b)
	0.025×10^5	25%	(b)	(b)	(b)	(b)	(b)	(b)	(b)	(b)	(b)	(b)
	0.050×10^5	50%	(b)	(b)	(b)	(b)	(b)	(b)	120	40	(b)	(b)
	0.025×10^5	100%	(b)	(b)	(b)	(b)	5	2.5				
2.54 cm (1.0 in.) chevron	3.750×10^5	2%	1950	120	97	30	11.1	8.2	60	26	95	25
	0.025×10^5	25%	100	50	2.6	2.6	2.3	2.1	28.5	25	20	12.5
	0.050×10^5	50%	(b)	(b)	0.75	0.5	0.61	0.57	40	26.5	1.7	1.6
	0.025×10^5	100%	67	33	0.88	0.75	0.88	0.75	20	10	(b)	(b)

[a]Measurements are indicated as number of cycles per 5×10^{-8} m^3 (number of cycles per drop of leakage).

The requirement established for leakage was a minimum of 25 cycles per 10^{-7} m^3 (25 cycles per 2 drops).

[b]No leakage observed during 5-min observation made each 1 hr of test.

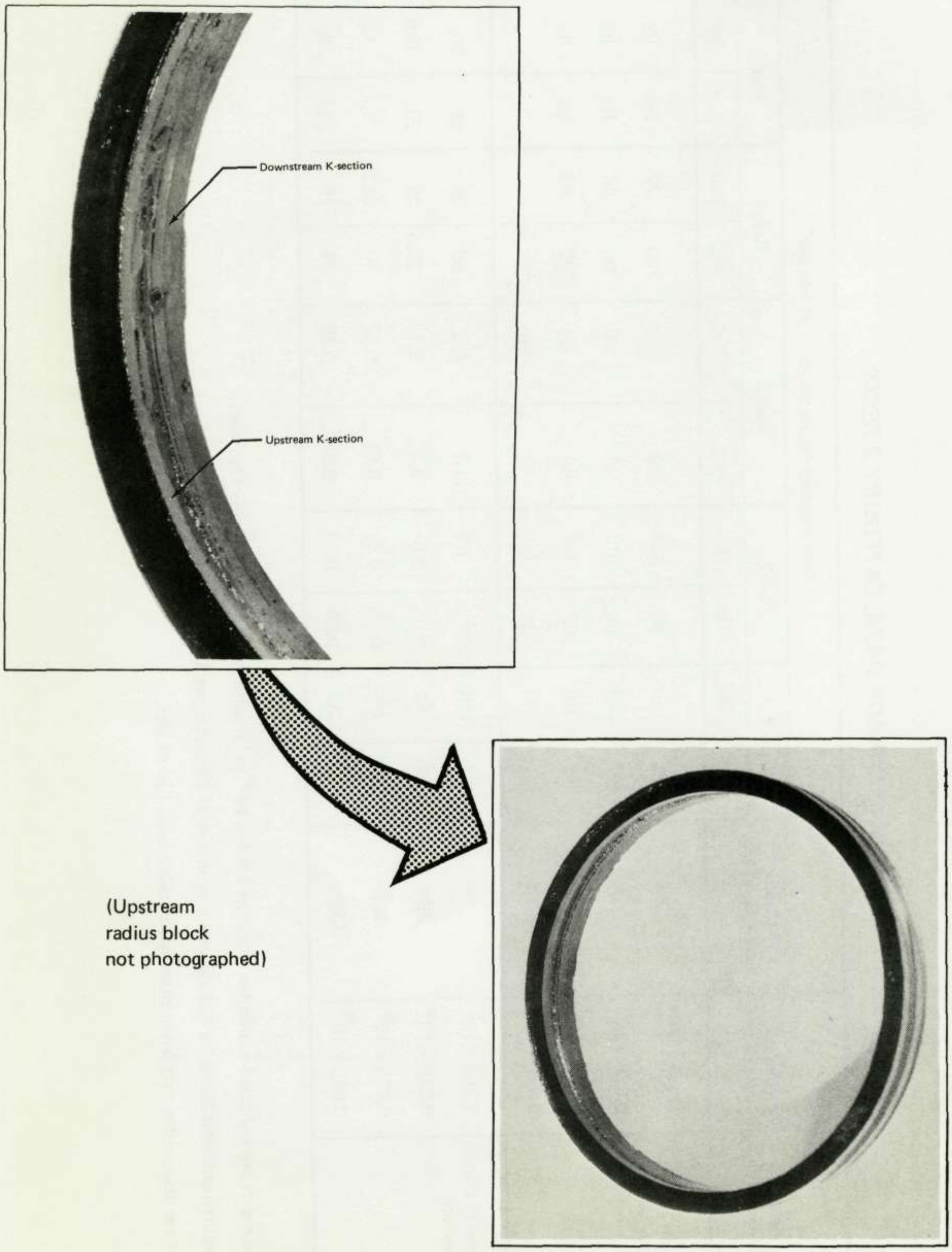
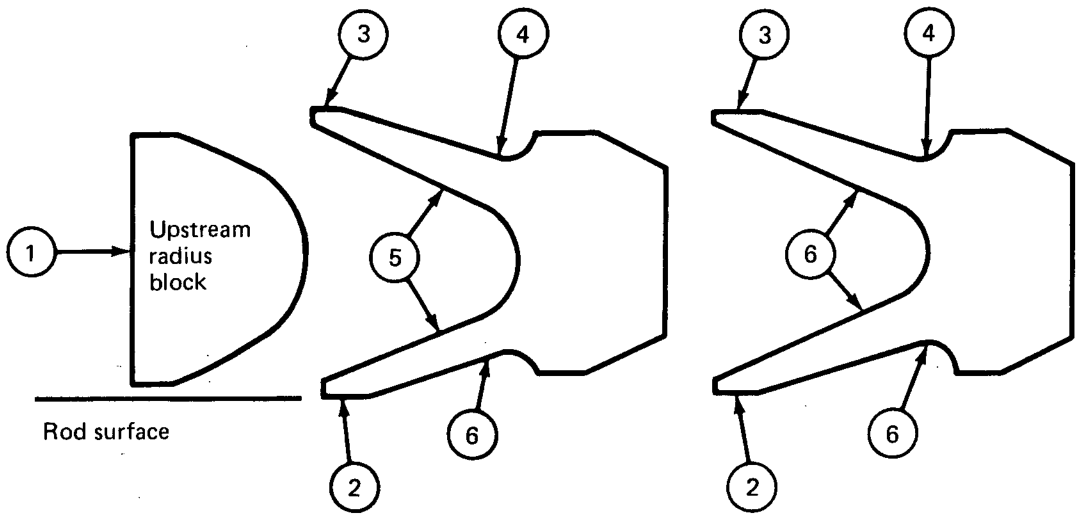


FIGURE 8.—6.35 CM (2.5 IN.) K-SECTION SEAL AFTER TEST



(1) No contact was noted, indicating that the gland was long enough so that the thermally expanding seal did not completely fill the cavity.

(2) Highly polished across entire surface, indicating wear had produced an extension of machined flat.

(3) Light contact area noted.

(4) Seal free of deposits.

(5) Light fluid residue not considered excessive.

(6) Heavy fluid residue deposits.

FIGURE 9.—6.35 CM (2.5 IN.) K-SECTION INSPECTION AFTER TEST

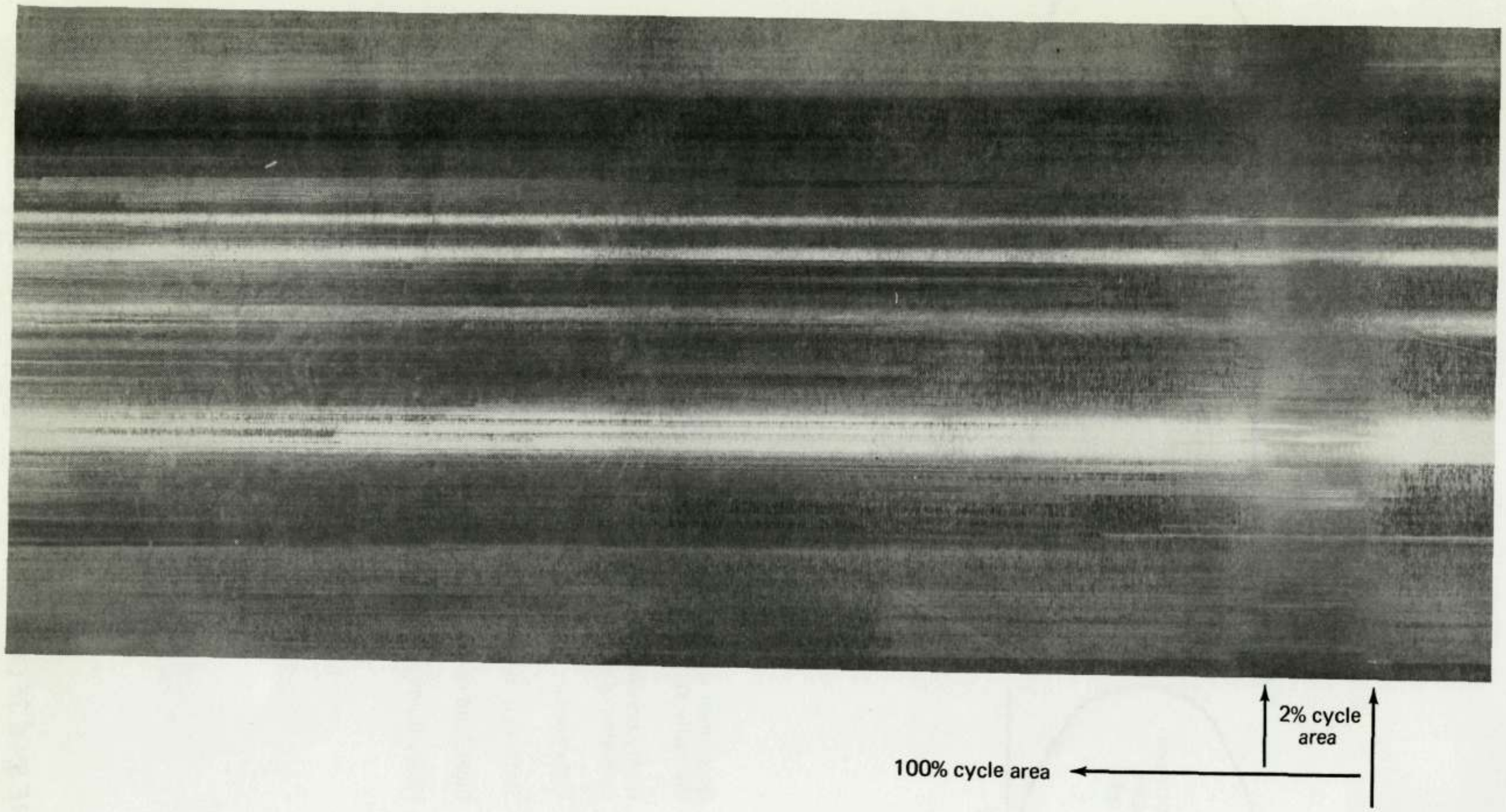


FIGURE 10.–6.35 CM (2.5 IN.) ACTUATOR ROD AFTER TEST

2.54 cm (1.0 in.) chevron seal.—The chevron seal assembly was noted to have a tight fit on the actuator rod and snug fit in the end cap cavity. Minor residue deposits were found on the seal and seal cavity. These were considerably less than those deposits noted on the 6.35 cm (2.5 in.) K-section seal. Visual inspection of the seal components with a microscope revealed no cracks or surface irregularities. The dynamic surfaces of both seal upstream and downstream elements were highly polished, with a uniform pattern. A photograph of the seal after test is shown in figure 11 and a detailed description of seal conditions is provided in figure 12. The actuator rod was in good condition, with only superficial longitudinal marks in the seal running area, figure 13.

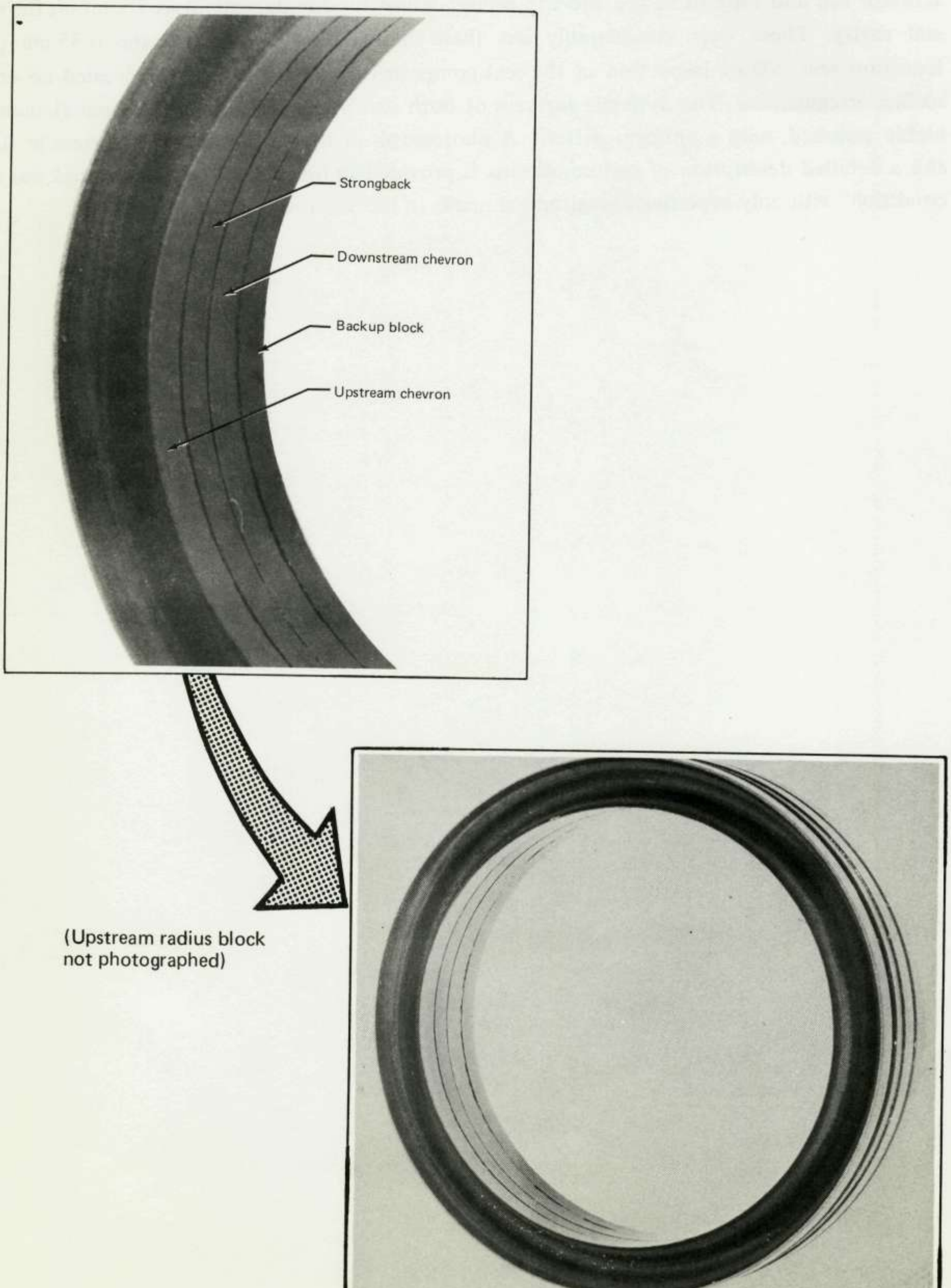
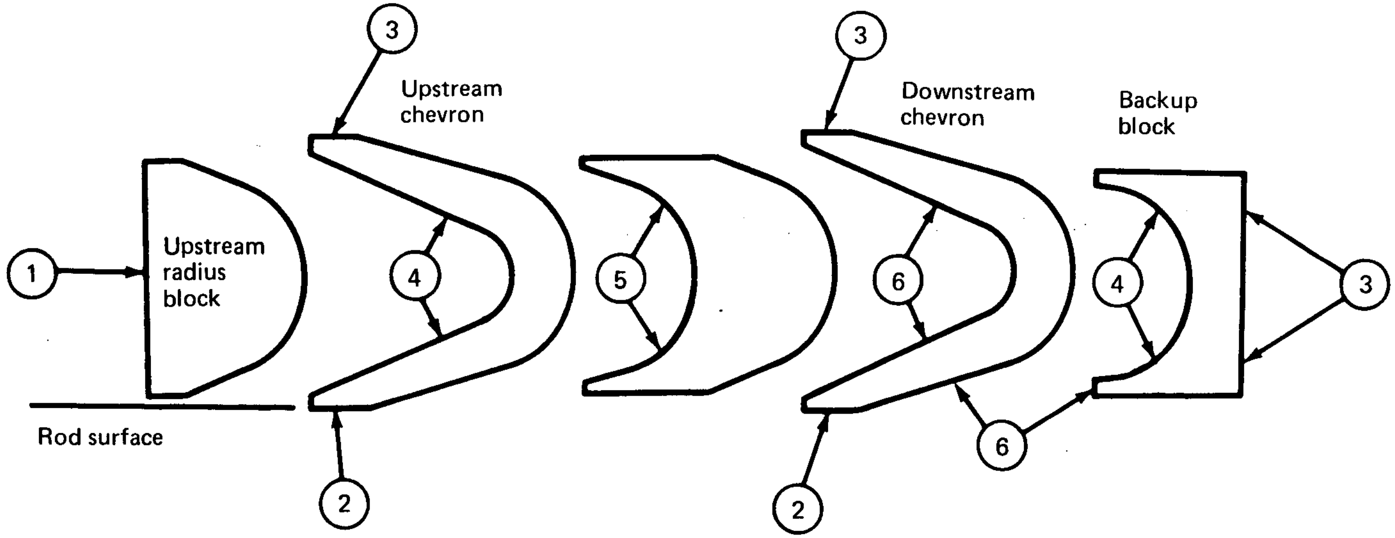


FIGURE 11.—2.54 CM (1.0 IN.) CHEVRON SEAL AFTER TEST



1. No contact was noted, indicating that the gland was long enough so that the thermally expanding seal did not completely fill the cavity.
2. Highly polished across entire surface, indicating wear had produced an extension of machined flat.
3. Light contact area noted.
4. Seal free of fluid residue deposits.
5. Light fluid residue deposits.
6. Heavy fluid residue deposits.

FIGURE 12.–2.54 CM (1.0 IN.) CHEVRON INSPECTION AFTER TEST

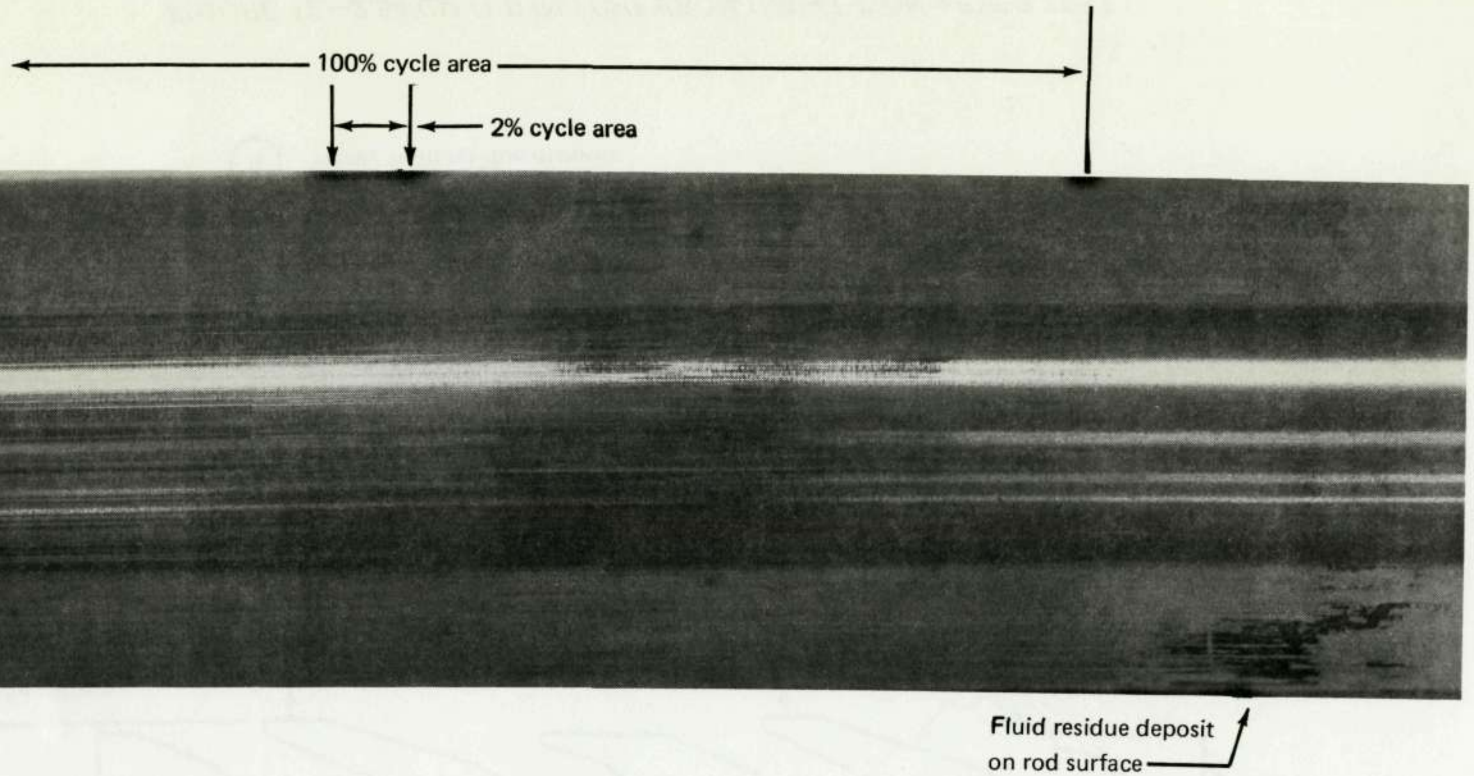


FIGURE 13.–2.54 CM (1.0 IN.) ACTUATOR ROD AFTER TEST

DISCUSSION OF RESULTS

The 6.35 cm (2.5 in.) K-section and the 2.54 cm (1.0 in.) chevron seals each accumulated a total of 5.625×10^6 short-stroke and 150 000 long-stroke cycles during the two categories of endurance tests. These cycles equate to 9375 hr of flight operation for a typical advanced aircraft system. An actual test time of 241.9 hr was accumulated at 478° K (400° F) and an additional 112.6 hr accumulated at 505° K (450° F).

The visual observation method of measuring second-stage leakage at the high test temperatures cannot account for fluid lost due to fluid film vaporization. Experience indicated the volume of vaporized fluid to be negligible. Even if an assumed vaporized volume were added to the measured leakage, the low leakage demonstrated by both configurations would be well within the acceptable leakage requirements for a linear rod seal application on an advanced aircraft.

The absence of cracks in either the upstream or downstream seal element of both designs indicates that the fatigue life for the seal assemblies was not exceeded during these tests. Previous experience with both seal designs showed that sealing integrity can be maintained by the downstream element of the assembly in the event that the upstream element fails (see ref. 3). The satisfactory condition of the seal contact surfaces and corresponding cycling area on the actuator rods demonstrates the compatibility of the polyimide seal materials and the hard chrome surface for future system applications.

The hard chrome actuator rods used for these tests were hand burnished lightly with polyimide SP-21 material after the final grinding to 6-7 rms. These actuator rods were in better condition after test than the unburnished actuator rods used during the reference 3 contract, which had the same machine finish. Due to the limited samples, it is not known whether the better performance can be attributed to the burnishing operation. Additional material compatibility and wear tests would be required to verify the advantages of burnishing with polyimide.

As noted, sealing at the actuator rod surfaces was interrupted by fluid residue accumulations on the rod surfaces. These deposits were due to decomposition of fluid films on the rod surfaces when these films were exposed to air at the 478° K (400° F) or 505° K (450° F) test temperatures. The residue was formed because the combination of time of exposure and maximum fluid temperature exceeded the reference 9 fluid thermal stability limits. The greater amount of deposits noted in the 6.35 cm (2.5 in.) K-section seal cavity than in the 2.54 cm (1.0 in.) chevron seal cavity was possibly related to the difference in seal gland materials. Experience with the polyolester family of fluids has shown the bearing bronzes to catalyze the degradation of the reference 9 fluid more rapidly than stainless steel materials. The module for the 6.35 cm (2.5 in.) K-section seal was made of aluminum-nickel-bronze, while the cavity for the 2.54 cm (1.0 in.) chevron seal was stainless steel, with an aluminum-nickel-bronze retainer outboard of the seal.

The scraper used in the 6.35 cm (2.5 in.) actuator was a spring-loaded polytetrafluorethylene (PTFE) part with 15% graphite fill. This scraper was ineffective in removing the fluid residue accumulation from the actuator rod once it had set. A metal scraper configuration would probably be more effective in preventing appreciable accumulations from forming.

First-stage seal performance was satisfactory during test, with the exception of the instance in the 2.54 cm (1.0 in.) actuator where rod deposits appeared to have interrupted the seal for a limited period.

CONCLUSION

Both the K-section and chevron seals tested were proven capable of maintaining sealing integrity for the conditions tested (fluid temperatures of 478° K (400° F) and 505° K (450° F) at 1.379×10^6 N/m^2 (200 psig). The established leakage characteristics and structural integrity would be adequate for application to advanced aircraft hydraulic system designs.

The demonstrated wear life of the SP-21 polyimide material at 478°-505° K (400°-450° F) was greater than the expected wear based on published wear data as a function of temperature. It appears, therefore, that the material allowables used in the seal design analysis for fatigue life were very conservative estimates.

The burnishing of the chrome actuator rod with the polyimide material prior to test was to some extent shown to be advantageous. Further material wear testing should be performed to determine whether appreciable reduction in polyimide wear rates can be achieved by this process.

Seal unit costs will be an important factor to industries considering applications for these seals. Further work should be conducted from both a material and fabrication process viewpoint to reduce seal costs.

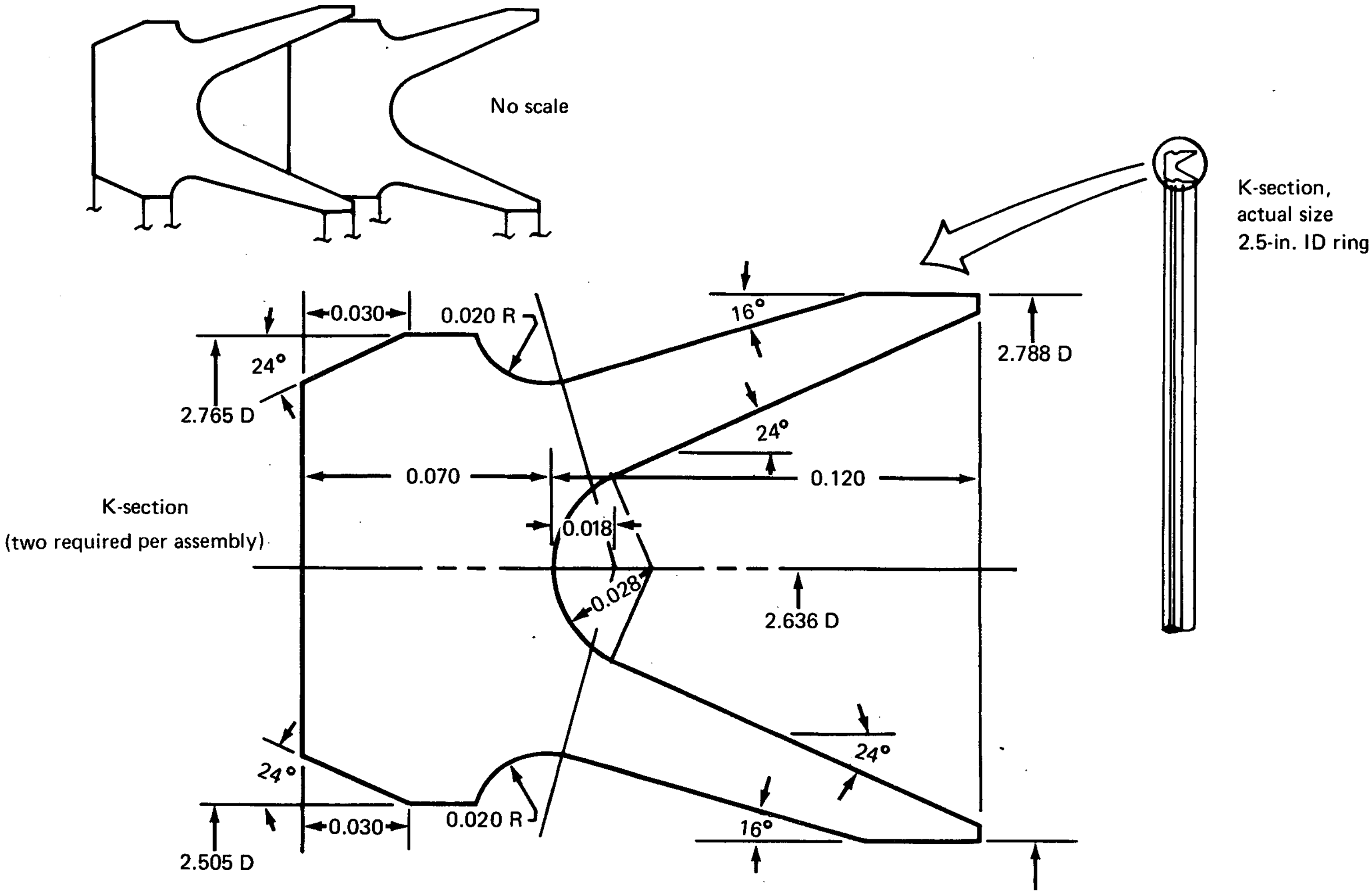
To utilize the full potential of these seals in solving difficult system designs, the engineer must have sufficient information at his disposal. Standardization of these seal configurations for the common actuator rod sizes is recommended.

APPENDIX A

SECOND-STAGE ROD SEAL ASSEMBLIES

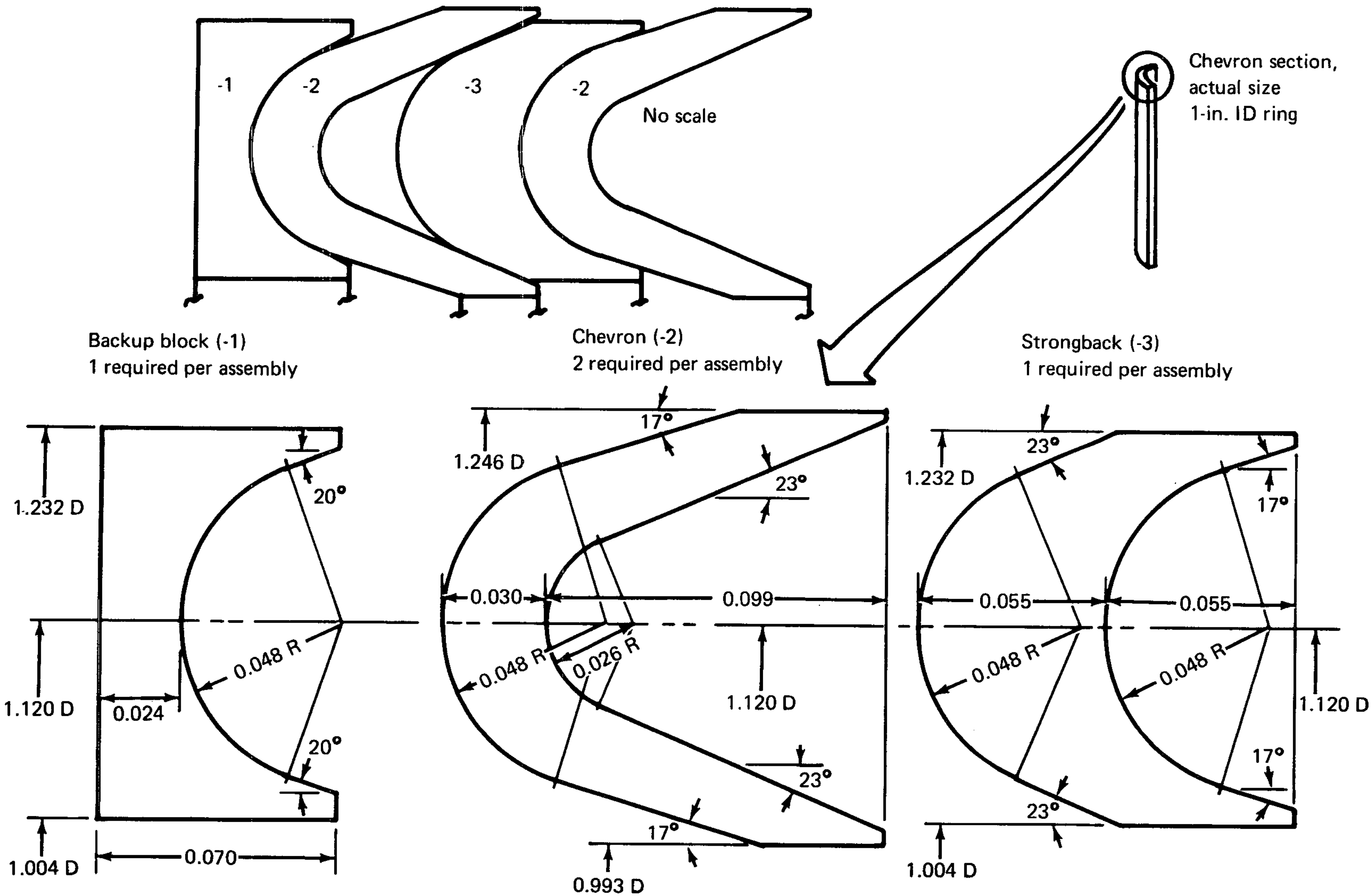
Figure 14 shows the design details of the 6.35 cm (2.5 in.) K-section seal configuration.

Figure 15 shows the design details of the 2.54 cm (1.0 in.) chevron seal configuration.



All dimensions in inches; no SI conversion was made on dimensioned parts.

FIGURE 14.—SECOND-STAGE ROD SEAL ASSEMBLY, 6.35 CM (2.5 IN.) K-SECTION

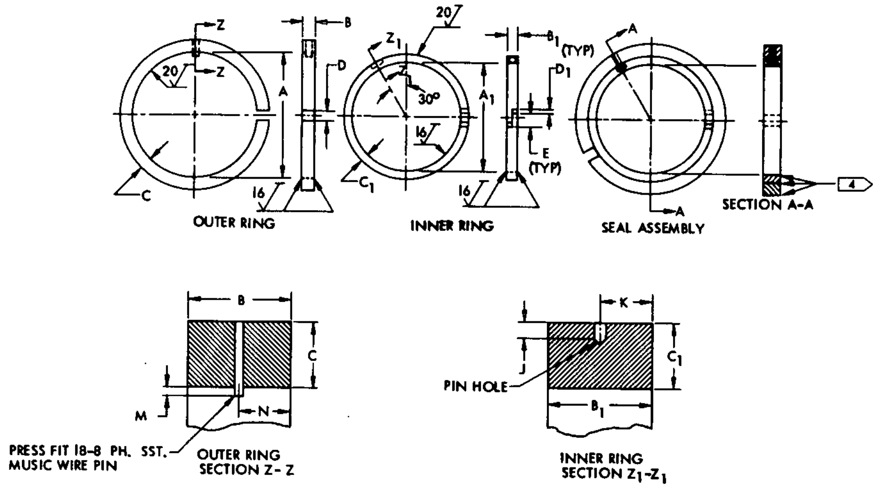


All dimensions in inches; no SI conversion was made on dimensioned parts.

FIGURE 15.—SECOND-STAGE ROD SEAL ASSEMBLY, 2.54 CM (1.0 IN.) CHEVRON

APPENDIX B

BOEING STANDARD, SEAL ASSEMBLY, ROD, METALLIC



TOLERANCES: ±.005 UNLESS OTHERWISE SPECIFIED

BOEING STD. NO. BACS11AM	KOPPERS PART NUMBER	OUTER RING A	OUTER RING B ±.0005	OUTER RING C	OUTER RING D 2	OUTER RING D 2 TOL	INNER RING A_1	INNER RING B_1 ±.0005	INNER RING C_1	INNER RING D_1 1	INNER RING D_1 1 TOL	E +.030 -.000	J +.005 -.000	K	M	N ±.001	PIN DIA	PIN HOLE	D 3
112	56695	.538		.023-.027	.115		.496		.019-.023										.047-.077
113	56698	.600		.023-.027	.115		.558		.019-.023										.047-.077
114	56701	.667		.025-.029	.115	-.000	.621		.021-.025	.020	+.005	.074							.047-.077
115	56704	.729		.025-.029	.115	+.020	.683		.021-.025		-.000				NO PIN				.047-.077
116	56707	.792		.027-.031	.125		.746		.021-.025										.052-.082
211	56710	.854		.027-.031	.125		.808		.021-.025										.052-.082
212	56713	.917		.028-.032	.135		.871	.0610	.028-.033										.060-.090
213	56716	.979	.0620	.028-.032	.135		.933		.028-.033										.060-.090
214	56719	1.041		.030-.035	.135		.996		.028-.033										.060-.090
216	56722	1.172		.035-.040	.150		1.121		.028-.033			.105	.013		.009				.062-.102
218	56725	1.303		.040-.045	.170		1.246		.028-.033	.035					.012				.072-.112
220	56728	1.434		.045-.050	.185		1.371		.029-.034					.0295		.031	.015	.025	.080-.120
222	56731	1.565		.048-.053	.200		1.496		.032-.037					.0325					.087-.127
326	56734	1.698		.053-.058	.220		1.621		.036-.041										.092-.142
327	56737	1.829		.057-.062	.240		1.746		.039-.044			.136							.102-.152
328	56740	1.955		.057-.067	.255		1.871		.041-.047	.040	+.015								.110-.160
329	56743	2.080		.057-.067	.255		1.996		.041-.047		.000		.018		.012				.110-.160
330	56746	2.217		.067-.077	.295		2.121		.043-.053						.017				.130-.180
331	56749	2.342	.0920	.067-.077	.295		2.246		.043-.053					.0445					.130-.180
332	56752	2.479		.074-.084	.320		2.371	.0910	.049-.059	.050				.0475		.046	.020	.035	.142-.192
333	56755	2.614		.078-.088	.320	-.000	2.496		.054-.064			.167							.142-.192
334	56758	2.741		.084-.094	.360	+.030	2.621		.055-.065										.157-.217
335	56761	2.874		.088-.098	.375		2.746		.059-.069	.055									.165-.225
336	56764	2.999		.088-.098	.375		2.871		.059-.069										.165-.225
337	56767	3.135		.097-.107	.415		2.995		.065-.075										.185-.245
338	56770	3.260		.097-.107	.415		3.120		.065-.075						.015				.180-.250
339	56773	3.397		.106-.116	.450		3.245		.071-.081				.022		.020		.025	.040	.197-.267
340	56776	3.522		.106-.116	.450		3.370		.071-.081										.197-.267
341	56779	3.659		.115-.125	.485		3.495		.077-.087										.215-.285
342	56782	3.784	.1235	.115-.125	.485		3.620	.1225	.077-.087		+.020			.0600					.215-.285
343	56785	3.923		.123-.133	.520		3.745		.084-.094		-.000	.190		.0630		.0615			.232-.302
344	56788	4.048		.123-.133	.520		3.870		.084-.094										.232-.302
345	56791	4.185		.133-.143	.560		3.995		.090-.100	.060									.242-.332
347	56794	4.447		.141-.151	.590		4.245		.096-.106										.257-.347
349	56797	4.709		.150-.160	.625		4.495		.102-.112										.275-.365
427	56800	4.972		.159-.169	.660		4.744		.109-.119				.037		.030				.277-.397
429	56803	5.234		.168-.178	.710		4.994		.115-.125		+.030	.220			.035		.030	.052	.302-.422
431	56806	5.484		.168-.178	.710		5.244		.115-.125		-.000								.302-.422
433	56809	5.748		.181-.191	.765	-.000	5.494		.122-.132										.332-.452
435	56812	5.998		.181-.191	.765	+.040	5.744		.122-.132										.332-.452

DATE 18 MAR 70 REV.

1	– –	2	– –
LIST OF ACTIVE SHEETS			

CODE IDENT NO. 81205

BAC S11AM SH 1 OF 2

SEAL ASSEMBLY, ROD, METALLIC

BAC S11AM SH 1 OF 2

BOEING STANDARD

PAGE 60.15.6.8.1

1 END CLEARANCE OF EACH RING TO BE MEASURED IN A GUAGE OF "A_1" ±.0005 DIAMETER.

2 END CLEARANCE OF EACH RING TO BE MEASURED IN A GUAGE OF "A" ±.0005 DIAMETER.

3 TENSION CONTROLLED BY OUTER RING GAP, RING IN FREE STATE.

4 I.D. EDGES OF INNER RING MAY HAVE A RADIUS OF .003 MAX FOR SIZES THROUGH BACS11AM345. SIZES LARGER THAN 345 MAY HAVE A RADIUS OF .005 MAX. O.D. EDGES OF OUTER RING MAY HAVE A RADIUS OF .015 MAX. INNER RING O.D. AND OUTER RING I.D. EDGES SHALL BE SHARP. ALL EDGES SHALL BE FREE OF BURRS.

MATERIAL: INNER: KOPPERS K-6E, ALLOY GREY IRON PER AMS 7310 EXCEPT CHROMIUM AND MOLYBDENUM ALLOYING ELEMENTS ADDED.
OUTER: 17-4PH CRES PER AMS 5643 OR AMS 5398, HARDNESS - R_c30-40.
PIN: 18-8 CRES PER AMS 5688.

FINISH: INNER RING ONLY. PARCO LUBRITE NUMBER 2 PER BAC5810, CLASS 1. THE RING SHALL THEN BE IMMEDIATELY IMMERSED IN HYDRAULIC FLUID WHICH MEETS THE REQUIREMENTS OF BMS3-10 AND PACKAGED WHILE DRIPPING WET WITH FLUID.

SURFACE ROUGHNESS: 63 RHR PER USAS B46.1 UNLESS OTHERWISE SPECIFIED. ROUGHNESS TO BE MEASURED PRIOR TO PARCO LUBRITE TREATMENT.

MARKING: EACH PACKAGE SHALL BE MARKED WITH THE SUPPLIER'S NAME, TRADEMARK OR CODE NUMBER, THE SUPPLIER'S PART NUMBER, AND THE BOEING STANDARD NUMBER.

CLEANING: PER KOPPERS COMPANY SPECIFICATION E-3803 TITLED "CLEANING AND PACKAGING PARTS TO BE USED IN PRECISION SEAL APPLICATIONS." CHLORINATED SOLVENT SHALL NOT BE USED IN THE CLEANING PROCESS.

PACKAGING: RING SETS CONSISTING OF AN OUTER AND INNER RING IN MATCHED SETS SHALL BE INDIVIDUALLY PACKAGED IN A HEAT SEALED POLYETHYLENE BAG. THE BAG SHALL THEN BE PLACED IN RIGID OR SEMI-RIGID BOXES.

INSPECTION: 100% INSPECTION BY THE MANUFACTURER. ASSEMBLY TO BE 100% LIGHT TIGHT BETWEEN INNER RING AND GAGE IN A GAGE OF "A_1" ±.0005 DIAMETER, AND 100% LIGHT TIGHT BETWEEN INNER AND OUTER RINGS FOR A DISTANCE EXTENDING 20° EITHER SIDE OF INNER RING STEP JOINT. LIGHT WHICH CAN BE PRESSED OUT WITH A RADIAL FORCE NOT EXCEEDING 5 LBS/INCH OF RING DIAMETER SHALL NOT BE CAUSE FOR REJECTION. EACH ASSEMBLY SHALL BE INSTALLED IN A TEST FIXTURE WITH A ROD FINISH OF 8 RHR AND A DIAMETER EQUAL TO THE MINIMUM ALLOWABLE PER MIL-G-5514, TABLE I, COLUMN "B". THE FOLLOWING TESTS SHALL BE CONDUCTED: MAXIMUM STATIC LEAKAGE USING MIL-F-7024, TYPE II AT ROOM TEMPERATURE AT 750 AND 4000 PSI SHALL NOT EXCEED 10 CC/MIN UP TO 2.500 INCH ROD DIAMETER, 25 CC/MINUTE FOR RODS 2.501 TO 5.000 INCH AND 50 CC/MINUTE FOR RODS OVER 5.000 INCH DIAMETER.

PROCUREMENT: KOPPERS COMPANY INCORPORATED, METAL PRODUCTS DIVISION, BUSH AND HAMBURG, BALTIMORE, MARYLAND 21203 (CODE IDENT NO. 75370)

THE SUPPLIERS LISTED AND THEIR AUTHORIZED DISTRIBUTORS ARE THE ONLY APPROVED SOURCES FOR THE ABOVE QUALIFIED PRODUCTS. CHANGES IN PRODUCT DESIGN OR QUALITY WITHOUT PRIOR BOEING APPROVAL MAY RESULT IN SUPPLIER DISQUALIFICATION. SUPPLIERS OF COMPETITIVE PRODUCTS MAY APPLY TO A MATERIEL DEPARTMENT OF THE BOEING COMPANY FOR QUALIFICATION.

USAGE AND APPLICATION INFORMATION

THESE SEAL RINGS ARE INTENDED AS ROD SEAL RINGS IN HYDRAULIC ACTUATORS WITH FLUID PER BMS 3-10 AT OPERATING TEMPERATURES OF 350° WITH EXCURSIONS TO 500°F. THESE SEALS TO BE USED WITH GROOVES PER BACD2040. THESE SEALS ARE NOT INTENDED FOR ZERO LEAKAGE APPLICATIONS.

DATE 18 MAR 70 REV.

SEE PREFACE FOR GENERAL USAGE NOTES.

BAC S11AM SH 2

PAGE 60.15.6.8.2

APPENDIX C

INSTRUMENTATION CALIBRATION AND DATA ACCURACY

Test instrumentation equipment calibrations are traceable through the Boeing flight test calibration laboratory to the National Bureau of Standards. Strain gage bridge-type transducers were calibrated to determine nonlinearity, hysteresis, and R-shunt calibration transfer values. Position transducers were end-to-end calibrated in place by a calibrated scale/visual technique.

PRESSURE

Transducer accuracy within	±0.75% full scale
Power and balance/conditioning within	±0.1% full scale
Oscillograph accuracy within	±2.0% full scale
Pressure measuring system accuracy (RSS) within	±2.1% full scale

DISPLACEMENT

Transducer accuracy within	±0.1% full scale
Signal conditioning within	±0.1% full scale
Oscillograph accuracy within	±2.0% full scale
Displacement measuring system accuracy (RSS) within	±2.0% full scale

TEMPERATURE

Thermocouple accuracy within	±1.11° K(±2° F)
Temperature recorder within	±2.2° K(±4.5° F)
Temperature measuring system accuracy (RSS) within	±2.5° K(±4.0° F)

REFERENCES

1. Lee, J.: High-Temperature Hydraulic System Actuator Seals for Use in Advanced Supersonic Aircraft. NASA CR-72354 (AIR-005301), Fairchild Hiller-Republic Aviation Division (contract NAS3-7264), September 1967.

2. Lee, J.: Development of High-Temperature Polyimide Rod Seals. NASA CR-72563 (AIR-23917), Fairchild Hiller-Republic Aviation Division (contract NAS3-11170), August 1969.

3. Waterman, A. W.: Application of Polyimide Rod Seals. NASA CR-120878, The Boeing Company (contract NAS3-14317), January 1972.

4. K-section Rod Seal, 2.5 Inch Inside Diameter. 64-14050, The Boeing Company (contract NAS3-14317), July 1971.

5. Chevron Rod Seal, 1.0 Inch Inside Diameter. 64-14047, The Boeing Company (contract NAS3-14317), July 1971.

6. Military Specification, Gland Design; Packings, Hydraulic, General Requirements for. MIL-G-5514F, January 1969.

7. Actuator Assembly–2.5 Inch Diameter (Test Only). 64-14051, The Boeing Company, August 1971.

8. Hydraulic Actuator–1.0 Inch Diameter (Test Only). 64-14052, The Boeing Company, August 1971.

9. Hydraulic Fluid Synthetic Base, Serviceable Over the Range -50° F to 450° F. BMS 3-10, The Boeing Company, April 1970.